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SPACE STATION *FREEDOM* COUPLING TASKS: AN EVALUATION OF THEIR SPACE OPERATIONAL COMPATIBILITY

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ABSTRACT

The development of Space Station *Freedom* tasks that are compatible with both telerobotic as well as extravehicular activity is a necessary redundancy in order to insure successful day to day operation. One task to be routinely performed aboard *Freedom* will be the changeout of various quick disconnect fluid connectors. In an attempt to resolve these potentially contradictory issues of compatibility, mock-ups of couplings suitable to both extravehicular as well as telerobotic activity have been designed and built. This paper discusses an evaluation performed at the Remote Operator Interaction Laboratory at NASA's Johnson Space Center which assessed the prototype coupling as well as three standard coupling designs. Data collected during manual and telerobotic manipulation of the couplings indicated that the custom coupling was in fact shown to be faster to operate and generally preferred over the standard coupling designs.

INTRODUCTION

After its completion, Space Station *Freedom* will continue to require a great deal of maintenance and support work in order to maintain daily operations. Dextrous manipulators including the Flight Telerobotic Servicer, the Special Purpose Dextrous Manipulator, and the Japanese Experimental Module Fine arm will not only be critical to the performance of these tasks but may actually be the primary system devoted to the execution of many of them.

Among the tasks to be commonly performed will be the coupling and uncoupling of fluid connectors designed to provide remote resupply of liquids and gases in orbit (NASA, 1989). This will be done using various quick disconnect (QD) couplings designed to mate and demate repeatedly without leakage. At present, several designs exist which allow the couplings to be quickly mated and demated by an extravehicular astronaut. While it is critical that these couplings be capable of manipulation by the suited astronaut, it is equally critical that these couplings be capable of successful operation with a telerobotic manipulator in order to reduce the likelihood of these hazardous extravehicular operations in the first place. Consequently, these couplings necessitate a design that is compatible with both modes of operation.

QD coupling designs and methods of actuation can vary widely. The coupling's contents, the amount of pressure it will have to sustain, the amount of flow it will need to accommodate, as well as several other factors all have a bearing on the coupling's final form. Clearly aboard *Freedom*, the varying conditions under which the different QDs operate will necessitate that their designs be different as well. Just as clear, however, is the concern that a proliferance of coupling designs will, at best, often result in uncertainty in a coupling's operation when encountered, and at worst, result in unsuccessful mating or even loss of fluid or pressure as a result of implementing the incorrect coupling process. Although the size and action of the couplings will obviously need to vary, it is preferable that a similar operation concept be shared over the coupling points aboard *Freedom* in order to reduce the likelihood of using the incorrect procedure.

It is widely held that in the vast majority of cases, a task that has been designed to be telerobotically compatible will be compatible with the extravehicular astronaut as well (Newport, 1989). This study, conducted in the Remote Operator Interaction Laboratory (ROIL) at NASA's Johnson Space Center (JSC), evaluated subjects' abilities to mate and demate QD couplings of varying design both telerobotically as well as manually. In a previous study assessing various telerobotic control modes, a manual condition was included as a representation of the optimal performance to strive for in the design of a space glove (Hannaford,1989). Therefore, the manual condition in this study is similarly included as a baseline to reasonably approximate extravehicular activity (EVA).

In collaboration with various telerobotic interface development facilities including the ROIL, Symetrics Inc. has been iteratively designing fluid couplings whose operation is intended to be telerobotically as well as EVA compatible. One of these iteratively designed couplings was among the four coupling designs evaluated in this investigation. Thus the hypothesis of this study proposes that the coupling designed to be telerobotically and EVA compatible will be mated and demated the most quickly and be most preferred subjectively for both the telerobotic as well as manual conditions.

METHOD

Subjects. Four subjects participated voluntarily in this study. In order to minimize learning effects associated with the various systems involved, all subjects had extensive experience with the telerobotic and viewing systems employed in the study. None of the subjects had any experience operating the QD couplings prior to their participation.

Apparatus. Three equipment systems were employed in the ROIL. These are: a telerobotic system, a viewing system, and a task support structure. The telerobotic system consisted of a Kraft force-reflecting master-slave manipulator. The viewing system consisted of three camera views displayed on two 21-inch monitors and one 9-inch monitor. The 21-inch monitors displayed close-up views of the couplings from both front and rear, while the 9-inch monitor displayed an overall view showing the subject the orientation of the manipulator to the task piece. The task support structure consisted of a 72-inch by 48-inch metal frame upon which each coupling was attached one at a time during testing. As demonstrated in Figure 1, the designs of the four couplings included in this study differed, as did their actuation.

Coupling A was demated by grasping the outer sleeve between the two flanges and applying axial force toward the flex hose. It was demated when enough force was applied to overcome the breakout force of the coupling. Mating occurred by aligning the coupling onto the nipple end and applying axial force until the outer sleeve locked back into place. This was the customized coupling designed specifically by Symetrics to be telerobotically and EVA compatible. The flanges of the outer spool-shaped sleeve were designed to be slightly wider than the telerobotic grippers. This allowed some compliance in grappling the fixture while still providing a sufficient brace in order to apply the axial force necessary for demating and mating. Another aspect of coupling A's design which did not exist on the other couplings was a chamfering of the entrance at a 45 degree angle in order to guide the nipple portion into the coupling. It was felt that these compliant features would also lead to enhanced manual operation of the coupling as well.

Coupling B had a very similar mechanism as coupling A. The narrow outer ring was pulled toward the flex hose until the breakout force of the coupling was overcome and the coupling was demated. Mating also occurred by aligning the coupling onto the nipple end and applying axial force until the coupling portion locked back into place.

Demating coupling C required depression of two detents, one on either side of a knurled aluminum ring. Once the detents were depressed, the aluminum ring would slide toward the flex hose and the coupling portion could be pulled away. Mating required aligning the coupling portion onto the nipple end and applying force axially until the detents engaged.

Coupling D had a lever-actuated demating process. The coupling's lever was pushed toward the hard mounted, nipple end. When the lever was pushed to a certain point (approximately 45 degrees), demating automatically occurred. Mating required aligning the coupling and applying axial force onto the nipple end until the lever restored itself to the vertical position.

It is important to note that the task performed in this study does not represent the entire coupling process. The experimental task consisted of, in effect, the soft-latch phase of the coupling process where the coupling is mated or demated but the actual flow of fluid has not been affected. With each of these couplings, the flow of fluid would need to be turned on or off in an additional step not included in the task. That phase of the coupling process would involve the use of an added tool or a modification to the end effector which would drive the coupling into the fully opened or closed position. Since that phase of the process has yet to be defined for Space

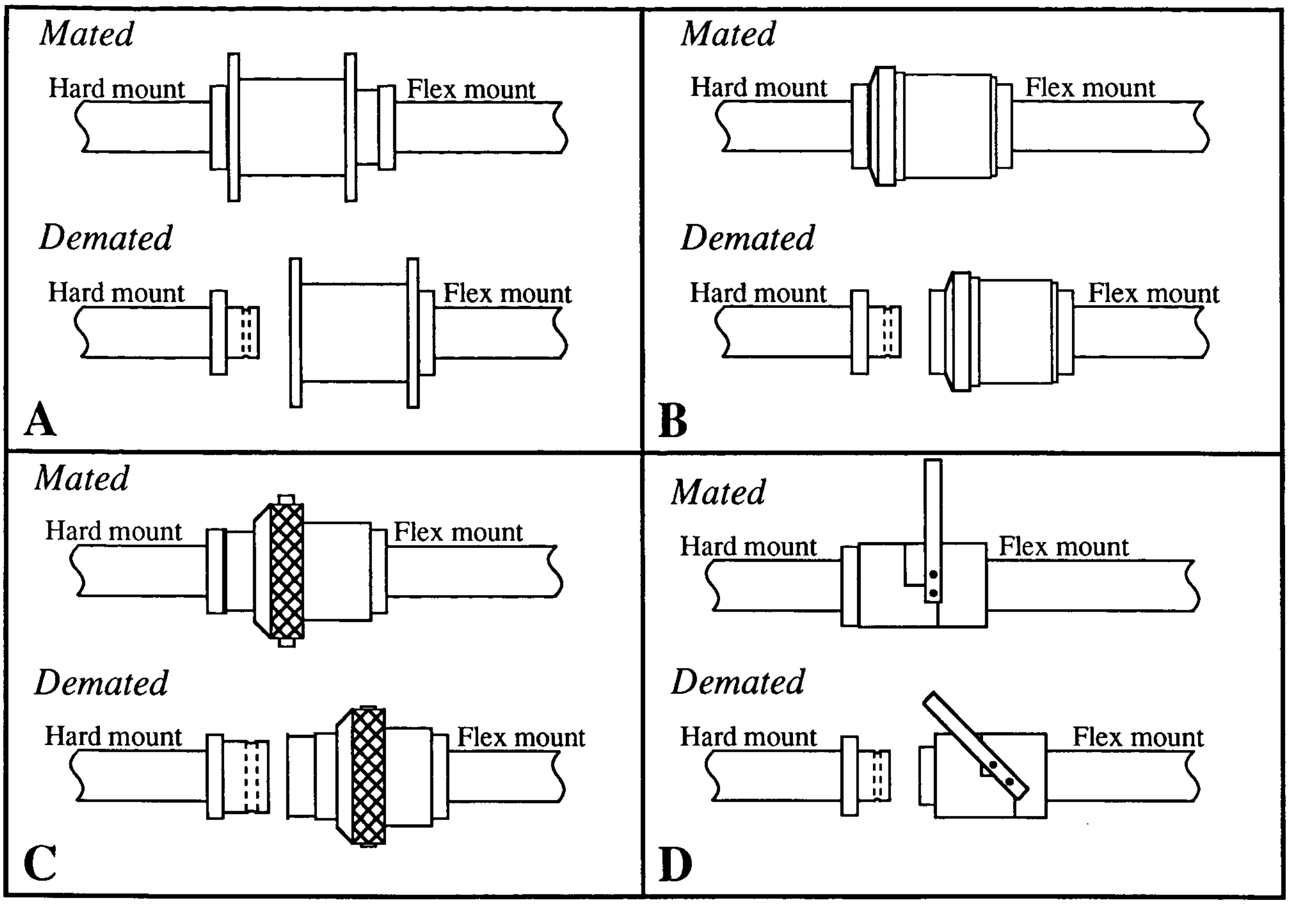

Figure 1. Schematic diagrams of the four couplings evaluated in this study.

Station *Freedom* operations, it was of interest to the experimenters to evaluate the compatibility of the mating and demating components of the task which could be addressed at this time.

Design. This study implemented a 2 modality (manual and telerobotic) by 4 coupling (couplings A, B, C, and D) within subjects design. Modality and coupling sequence was counterbalanced as demonstrated in Table 1.

Procedure. To begin each testing session, subjects were introduced to the purpose and procedure of the study as well as the basic layout of the cameras, task, and robotic system. Since subjects were already familiar with the operation of the robotic and viewing systems employed in the ROIL, no instruction was necessary regarding these aspects of the task.

Subjects began the session by manipulating a coupling either manually or telerobotically depending on their particular counterbalancing sequence. Each coupling was demated and mated three times in each modality. The experimenter kept performance time by means of a hand stopwatch and recorded those times on a data collection sheet where errors were logged as well. An error was counted only if the

Table 1. Counterbalancing sequence for couplings and modality across subjects (M = manual condition, T = telerobotic condition).

Subject	QD Coupling Sequence							
	1		2		3		4	
	Coup. A		Coup. B		Coup. D		Coup. C	
1	M	T	T	M	M	T	T	M
	Coup. B		Coup. C		Coup. A		Coup. D	
2	T	M	M	T	T	M	M	T
	Coup. C		Coup. D		Coup. B		Coup. A	
3	M	T	T	M	M	T	T	M
	Coup. D		Coup. A		Coup. C		Coup. B	
4	T	M	M	T	T	M	M	T

coupling portion was dropped. Timing would then stop while the experimenter reset the coupling and would restart as soon as the subject brought the arm back into motion. Following a set of three trials with each coupling, subjects filled out a short questionnaire with rating scales concerning workload, discomfort, as well as various task related issues. Once all the couplings had been completed, subjects filled out a final questionnaire for each modality where they rated the couplings in comparison to one another.

RESULTS AND DISCUSSION

Analysis of Variance performed on the data showed trends in both the performance as well as subjective data. Table 2 presents the group means for many of the performance and subjective measures. Due to the very few number of errors occurring in any of the trials, analysis of the error data resulted in no significant findings and is not discussed.

It was hypothesized that as a result of the compliant structures built into coupling A, demating and mating it would be faster than other couplings without these structures built into them. Data from the telerobotic trials showed that differences between performance time across the couplings was significant ($F(3,3) = 4.372, p < .05$). A Duncan's pairwise comparison performed on the data showed that the source of significance came largely from coupling C being significantly slower than all other couplings' performance time. Due primarily to the small variance in the manual condition, differences in performance time did not reach significance for these trials. A Duncan's pairwise comparison on these data, however, did show that performance time for coupling A was significantly faster than coupling C. As anticipated, it appears that for both modalities, coupling A was faster - in some cases significantly faster - to demate and mate than the other couplings.

It was also felt that subjective reactions to the couplings would show preference for the custom coupling in both modalities. The overall rating data were collected on seven point scales with 1 corresponding to "completely acceptable" and 7 corresponding to "completely unacceptable." As shown in Table 2, these data revealed reliable differences, this time for both telerobotic as well as manual ratings. The data regarding the telerobotic preference revealed an $F(3,3) = 7.981$ with a $p < .01$. Pairwise comparisons showed that couplings A and B were rated significantly more acceptable than coupling C, while coupling A was significantly more acceptable than coupling D. For the manual ratings the data showed that $F(3,3) = 8.007$, with $p < .01$. In this case pairwise comparisons indicated that coupling C was significantly less acceptable than all others. The comparable ratings attributed to couplings A and B appeared the result of their similar mechanisms and operation. The shape of the outer sleeve and coupling A's chamfering was all that varied between the two.

Table 2. Group means for performance and subjective measures.

Measure	Modality of Operation							
	Telerobotic				Manual			
	A	B	C	D	A	B	C	D
Perform. Time per Trial (sec.)	66	77	450	168	2.4	3.7	6.4	3.8
Overall Rating (1 to 7)	1.5	2.0	5.3	3.8	1.8	2.5	5.0	2.5
Grip Acceptability (1 to 7)	1.3	2.8	3.5	2.8	1.3	1.8	3.8	1.3
Mental Workload (1 to 10)	3.0	2.5	6.8	4.0	Not Addressed			
Phys. Discomfort (1 to 7)	2.5	1.5	3.8	2.5				

Using the same seven point scale described above, data regarding the acceptability of obtaining the proper grip did not reach significance for the telerobotic condition, although the pairwise comparisons did show that coupling A was rated significantly more acceptable than coupling C. For the manual condition this difference did reach significance, $F(3,3) = 5.368, p < .05$, with the comparisons among the means indicating that coupling C was significantly less acceptable than all three other couplings.

After the telerobotic trials, data were also collected on mental workload and physical discomfort. Data from a Modified Cooper-Harper mental workload rating scale reached significance, $F(3,3) = 3.860$, $p < .05$. The pairwise comparisons showed that couplings A and B were rated significantly less mentally taxing than coupling C. Data from either question addressing physical discomfort did not reach significance although the pairwise comparisons tended to show couplings A and B as less demanding than coupling C. These effects seemed the result of the rather straight-forward mechanism implemented on couplings A and B. Subjects only had to grab and pull to demate couplings A and B, while coupling C required depression of detents on either side of the detention sleeve. This orientation was often very difficult to achieve with the robotic grippers, typically requiring repeated attempts before demate finally occurred. Issues of mental workload and physical discomfort were not addressed after the manual trials due to their very short duration.

CONCLUSION

Of the couplings included in this study, the different operational components resulted in varying reactions from the subjects.

Regarding the demate process, subjects felt coupling D included an attractive feature by requiring little force to demate, achieving it simply by forcing the lever over. However, maintaining control of the coupling portion after demate proved difficult for teleoperation, although somewhat easier for manual operation. Demating coupling C showed that depression of detents is a very delicate operation to perform with the telerobot and to some extent, to perform manually as well. Without some method of fixing the orientation of the detents, it is very difficult to engage both at the same time, particularly with the telerobot. This was compounded by the fact that the depression had to be combined with the axial force necessary to demate. Because of coupling B's small outer ring, demating was at times found to be clumsy with it as well. This was particularly the case for the telerobotic condition, but at times the manual condition was awkward as well.

Mating the couplings proved, on the whole, a far simpler process. Couplings B and D required close alignment which, when met, resulted in a very straight-forward mating process. Coupling C incorporated a longer nipple portion to the coupling. This assisted operation in both modalities by helping to guide the coupling into the mated position when the axial force was applied.

While coupling A did appear the better design in this evaluation, there clearly were facets which could be improved. Although the large flanges on the outer sleeve assisted in mating, they also might allow the telerobot or EVA astronaut to accidentally bump or deactivate the coupling prior to full actuation. Also, the chamfering performed on the entry of the coupling was perhaps angled too far. The 45 degree entrance guided the nipple portion into the coupling, but allowed sufficient misalignment such that the coupling often bound just prior to fully mating. Symetrics has recognized these concerns and has provided the ROIL with a coupling addressing these issues by making two changes in the design. New shorter flanges still allow necessary support for the axial forces required, but greatly reduce the likelihood of accidental deactivation. The entry to the coupling was also chamfered to approximately 30 degrees rather than 45. This assisted in guiding the nipple into the coupling but reduced the potential for binding by lessening the amount of misalignment possible.

The purpose of this study was not to conceive the final coupling design. Rather, it was intended as a step along an iterative process. The newly modified coupling will be included in a series of further controlled as well as subjective evaluations. This is part of ongoing work in the ROIL designed to enhance the overall interface by improving design at both the teleoperator and telerobot ends of the system.

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